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Mathematical Modeling and Simulation of Photovoltaic Cell using Matlab-Simulink Environment

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ABSTRACT

Photovoltaic power supplied to the utility grid is gaining more and more visibility while the world's powers demand is increases. Growing demand, advancements in semiconductor technology and magnetic materials such as high frequency inductor cores, has a significant impact on PV inverter topologies and their efficiencies, on the improvement of the control circuits on the potential of costs reduction. The user naturally wants to operate the Photovoltaic (PV) array at its highest energy conversion output by continuously utilizing the maximum available solar power of the array. The electrical system PV modules are powered by solar arrays requires special design considerations due to varying nature of the solar power generated resulting from unpredictable and sudden changes in weather conditions which change the solar irradiation level as well as the cell operating temperature. This paper, a mathematical model of a Photovoltaic (PV) cell used matlab-simulink environment, is developed and presented. The model is developed using basic circuit equations of the photovoltaic solar cells including the effects of solar irradiation and temperature changes. The main objective is to find the parameters of the nonlinear *I–V* equation by adjusting the curve at three points: open circuit, maximum power, and short circuit. the method finds the best *I–V* equation for the single-diode photovoltaic (PV) model including the effect of the series and parallel resistances

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1. INTRODUCTION

A photovoltaic system converts sunlight into electricity. The basic device of a photovoltaic system is the photovoltaic cell. Cells may be grouped to form panels or modules. Panels can be grouped to form large photovoltaic arrays. The term *array* is usually employed to describe a photovoltaic panel (with several cells connected in series and/or parallel) or a group of panels. Most of time one are interested in modeling photovoltaic panels, which are the commercial photovoltaic devices. This paper focuses on modeling photovoltaic modules or panels composed of several basic cells. The term *array* used henceforth means any photovoltaic device composed of several basic cells. In the Appendix at the end of this paper there are some explanations about how to model and simulate large photovoltaic arrays composed of several panels connected in series or in parallel.

All though solar cells prices were very expensive at the beginning, they become cheaper during last decade due to developing manufacturing processes, so that it is expected that the electricity from PV arrays will be able to compete with the conventional ones by the next decade. Since a PV array is an expensive system to build, and the cost of electricity from the utility grid, the user of such an expensive system naturally wants to use all of the available output power. Therefore, PV array systems should be designed to operate at their maximum output power levels for any temperature and solar irradiation level at all the time.

The first purpose of this paper is to present a brief introduction to the behavior and functioning of a PV device and write its basic equations, without the intention of providing an in depth analysis of the PV phenomenon and the semiconductor physics. The introduction on PV devices is followed by the modeling and simulation of PV arrays, which is the main subject of this paper.

The performance of a PV array system depends on the operating conditions as well as the solar cell and array design quality. The output voltage, current and power of PV array vary as functions of solar irradiation level, temperature and load current. Therefore the effects of these three quantities must be considered in the design of PV arrays so that any change in temperature and solar irradiation levels should not adversely affect the PV array output to the load/utility, which is either a power company utility grid or any stand alone electrical type load.Salamh and Dagher have proposed a switching system that changes the cell array topology and connections or the structural connections of the arrays to establish the required voltage during different periods of a day. The PVA model proposed in this paper is circuitry based model to be used with simulink.

2. HOW A PV CELL WORKS

A photovoltaic cell is basically a semiconductor diode whose *p–n* junction is exposed to light [1], [2]. Photovoltaic cells are made of several types of semiconductors using different manufacturing processes. The monocrystalline and polycrystalline silicon cells are the only found at commercial scale at the present time. Silicon PV cells are composed of a thin layer of bulk Si or a thin Si film connected to electric terminals. One of the sides of the Si layer is doped to form the *p–n* junction. A thin metallic grid is placed on the Sun-facing surface of the semiconductor. Fig. 1 roughly illustrates the physical structure of a PV cell. The incidence of light on the cell generates charge carriers that originate an electric current if the cell is shortcircuited [2]. Charges are generated when the energy of the incident photon is sufficient to detach the covalent electrons of the semiconductor—this phenomenon depends on the semiconductor material and on the wavelength of the incident light.

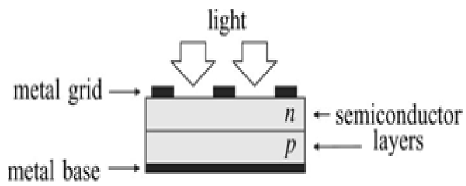

Fig. 1 structure of a PV cell

Basically, the PV phenomenon may be described as the absorption of solar radiation, the generation and transport of free carriers at the *p–n* junction, and the collection of these electric charges at the terminals of the PV device [3], [4]. The rate of generation of electric carriers depends on the flux of incident light and the capacity of absorption of the semiconductor. The capacity of absorption depends mainly on the semiconductor bandgap, on the reflectance of the cell surface (that depends on the shape and treatment of the surface), on the intrinsic concentration of carriers of the semiconductor, on the electronic mobility, on the recombination rate, on the temperature, and on several other factors. The solar radiation is composed of photons of different energies. Photons with energies lower than the bandgap of the PV cell are useless and generate no voltage or electric current. Photons with energy superior to the bandgap generate electricity, but only the energy corresponding to the bandgap is used—the remainder of energy is dissipated as heat in the body of the PV cell. Semiconductors with lower bandgaps may take advantage or a larger radiation spectrum, but the generated voltages are lower [5]. Si is not the onl y, and probably not the best, semiconductor material for PV cells, but it is the only one whose fabrication process is economically feasible in large scale. Other materials can achieve better conversion efficiency, but at higher and commercially unfeasible costs.

3. PHOTOVOLTAIC MODELING

A. Equivalent Electric Circuit of Photovoltaic Cell

Fig. 2 shows the equivalent circuit of the ideal photovoltaic cell. The basic equation from the theory of semiconductors [1] that mathematically describes the I-V characteristic of the ideal photovoltaic cell is:

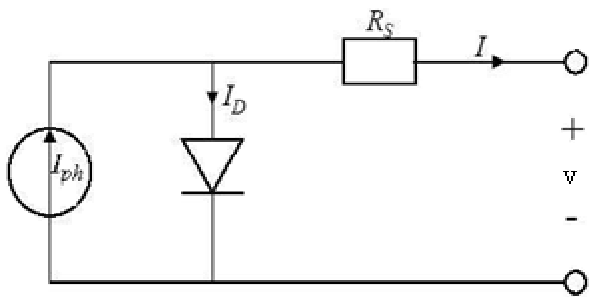

Fig. 2 Equivalent electric circuit of photovoltaic cell

$$I = I_{pvcell} - \underbrace{I_{ocell}\left[\exp\left(\frac{qv}{AKT}\right) - 1\right]}_{\text{Id}} \quad (1)$$

Where the symbols are defined as follows:

I_{pv}, cell is the current generated by the incident light (it is directly proportional to the Sun irradiation),
I_d is the Shockley diode equation,
I_0,cell is the reverse saturation or leakage current of the diode,
q is the electron charge (1.60217646 × 10−19 C),
k is the Boltzmann constant (1.3806503 × 10−23 J/K), T (in Kelvin) is the temperature of the *p–n* junction,
A is the diode ideality constant.
e: electron charge (1.602 × 10-19 C).
Ic: cell output current, A.
Iph: photocurrent, function of irradiation level and junction
temperature (5 A).
I0: reverse saturation current of diode (0.0002 A).
Rs: series resistance of cell (0.001 Ω).
Tc: reference cell operating temperature (20 °C).
Vc: cell output voltage, V

The basic equation (1) of the elementary photovoltaic cell does not represent the I-V characteristic of a practical photovoltaic array. Practical arrays are composed of several connected photovoltaic cells and the observation of the characteristics at the terminals of the photovoltaic array requires the inclusion of additional parameters to the basic equation [1]:

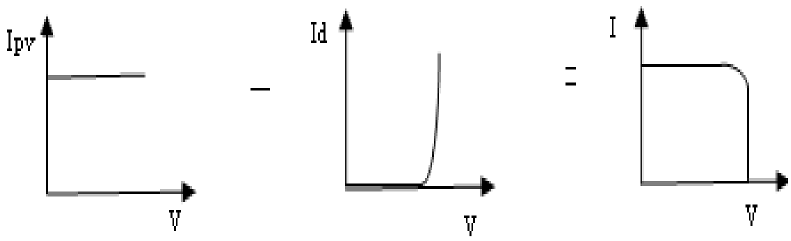

Fig. 3 Characteristic I-V curve of the photovoltaic cell.

The net cell current I is composed of the light-generated current Ipv and the diode current I_d. Where Ipv and I0 are the photovoltaic and saturation currents of the array and Vt = NskT/q is the thermal voltage of the array with Ns cells connected in series. Cells connected in parallel increase the current and cells connected in series provide greater output voltages. If the array is composed of Np parallel connections of cells the photovoltaic and saturation currents may be expressed as: Ipv=Ipv,cellNp, I0=I0,cellNp. In (2) Rs is the equivalent series resistance of the array and Rp is the equivalent parallel resistance. This equation originates the I-V curve seen in Fig. 3, where three *remarkable points* are highlighted: short circuit (0, Isc), maximum power point (Vmp, Imp) and open-circuit (Voc, 0).

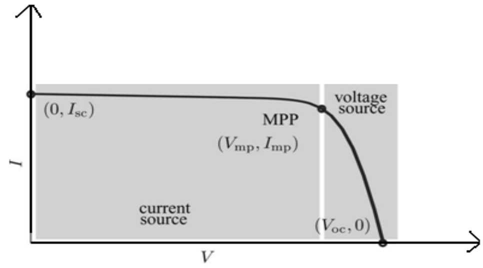

Fig. 4. Characteristic *I–V* curve of a practical PV device and the three *remarkable points*: short circuit (0, *I*sc), MPP (*V*mp, *I*mp), and open circuit (*V*oc , 0).

Let (1) be the benchmark model for the known operating temperature Tc and known solar irradiation level Sc as given in the specification. When the ambient temperature and irradiation levels change, the cell operating temperature also changes, resulting in a new output voltage and a new photocurrent value. The solar cell operating temperature varies as a function of solar irradiation level and ambient temperature. The variable ambient temperature Ta affects the cell output voltage and cell photocurrent. These effects are represented in the model by the temperature coefficients CTV and CTI for cell output voltage and cell photocurrent, respectively, as:

$$C_{TV} = 1 + \beta_T(Ta - Tx) \quad (2)$$

$$C_{TI} = 1 + \frac{\gamma t}{Sc}(Tx - Ta) \quad (3)$$

Where, βT = 0.004 and γT = 0.06 for the cell used and Ta=20 oC is the ambient temperature during the cell testing. This is used to obtain the modified model of the cell for another ambient temperature Tx. Even if the ambient temperature does not change significantly during the daytime, the solar irradiation level changes depending on the amount of sunlight and clouds. A change in solar irradiation level causes a change in the cell photocurrent and operating temperature, which in turn affects the cell output voltage. If the solar irradiation level increases from Sx1 to Sx2, the cell operating temperature and the photocurrent will also increase from Tx1 to Tx2 and from Iphl to Iph2, respectively. Thus the change in the operating temperature and in the photocurrent due to variation in the solar irradiation level can be expressed via two constants, CSV and CSI, which are the correction factors for changes in cell output voltage VC and photocurrent Iph, respectively:

$$C_{sV} = 1 + \beta_T \alpha_s(Sx - Sc) \quad (4)$$

$$C_{sI} = 1 + \frac{1}{Sc}(Sx - Sc) \quad (5)$$

where SC is the benchmark reference solar irradiation level during the cell testing to obtain the modified cell model. Sx is the new level of the solar irradiation. The temperature change, Δ*TC,* occurs due to the change in the solar irradiation level and
is obtained using

$$\Delta_{Tc} = 1 + \alpha_s(Sx - Sc) \quad (6)$$

The constant αS represents the slope of the change in the cell operating temperature due to a change in the solar irradiation level [1] and is equal to 0.2 for the solar cells used. Using orrection factors C_{TV}, C_{TI}, Csv and Cs_I, the new values of the cell output voltage V_{cx} and photocurrent Iphx are obtained for the new temperature Tx and solar irradiation Sx as follows:

$$V_{cx} = C_{TV} C_{sV} V_c \quad (7)$$

$$I_{phx} = C_{TI} C_{SI} I_{ph} \quad (8)$$

V_c and I_{ph} are the benchmark reference cell output voltage and reference cell photocurrent, respectively. The resulting I-V and P V curves for various temperature and solar irradiation levels were discussed and shown in [6, 8, 9], therefore they are not going to be given here again.

$$P_c = V_c\left(I_{ph} - I_a * \exp(\frac{q}{KT}V_c - I_o)\right) \quad (9)$$

$$I_c = I_{ph} - I_0 * \exp\left(\frac{q}{KT}V_c - I_0\right) \quad (10)$$

If we connect a resistive load R to cell then working point of cell will be on crossing point volt-ampere characteristic of cell and load characteristic. Volt-ampere characteristic of load is a straight line with slope 1/R. If value of R is too low, the working point is in area between M and N where cell behaves like constant current source. It is more or less short circuit current. But if value of R is high, the working point is in area between P and S where cell behaves like constant voltage source. It means about a open circuit voltage. Connection with optimal resistance Ropt means that PV cell generates maximum output power which is given to product of voltage Um and current Im. Working points where the maximum of power is and efficiency is in the flexion of voltampere characteristic.

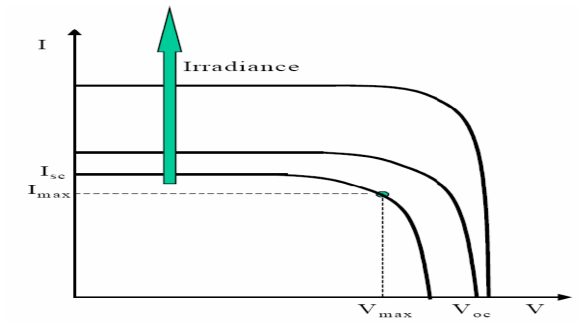

Fig. 5 Influence of the ambient irradiation on the cell Characteristics

In Fig. 5, an voltampere characteristics of a PV cell for only a certain ambient irradiation Ga and only a certain cell temperature Tc is illustrated. The influence of the ambient irradiation Ga and the cell temperature Tc on the cell characteristics in presented in Fig. 4.

Fig. 6 shows that the open circuit voltage increases logarithmically with the ambient irradiation while the short circuit current is a linear function of the ambient irradiation. The arrow shows in which sense the irradiation and the cell temperature, respectively, increase. The influence of the cell temperature on the voltampere characteristics is illustrated in Fig 4. The dominant effect with increasing cell´s temperature is the linear decrease of the open circuit voltage, the cell being thus less efficient. The short circuit current slightly increases with cell temperature. For practical use, PV cells can be electrical connected in different ways:

series or parallel. Figure 5 and Figure 6 present how the voltampere curve is modified in the cases when two identical cells are connected in series and in parallel.

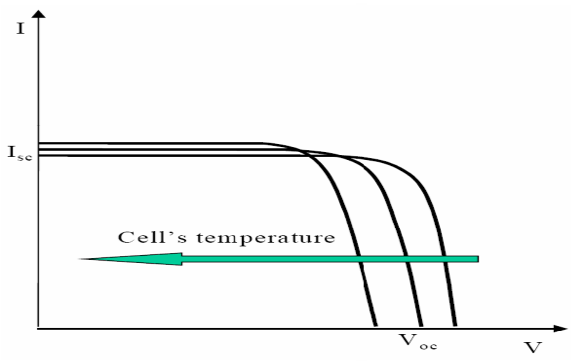

Fig. 6 Influence of the cell temperature on the cell Characteristics

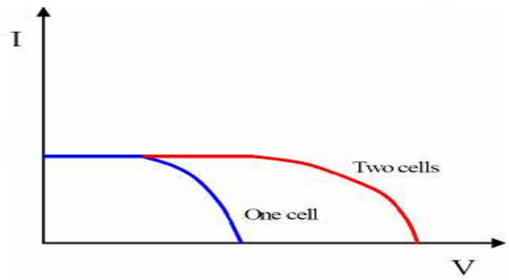

Fig. 7. Series connection of identical cells

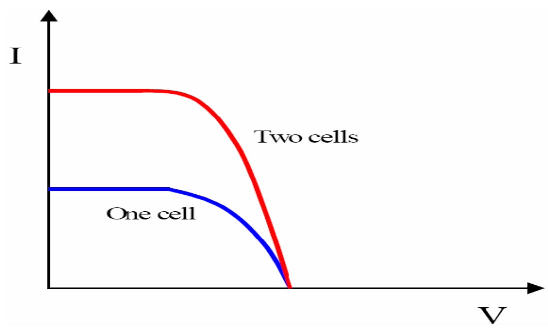

Fig. 8. Parallel connection of identical cells

It is seen that voltampere characteristics of series interconnected cells can be found by adding, for each current, the different voltages of the individual cells. On the other hand, for parallel cells the currents of the individual cells must be added at each voltage in order to find the overall volt-ampere curve.

4. RESULTS AND ANALYSIS

The simulation results of the individual system components and overall results after integrating the different components are presented below. The PV cell temperature is maintained constant at 25^0C and the solar intensity is varied in steps up to the rated value of 10 Wcm^{-2}. It is seen from the figure .9 that for a constant solar intensity the current remains constant with increasing voltage up to 100Volts after which it decreases. It is further observed that the current increase with increasing intensity thereby increasing the power output of the solar cell.

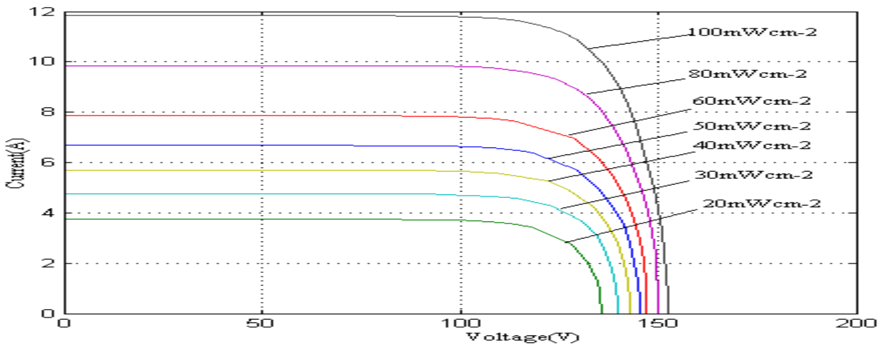

Fig. 9 V-I characteristics of PV module for various solar intensities at rated cell temperature.

The effect of temperature variations on the V-I characteristics of the PV cell is shown in figure. 8. A marginal variation in current is observed for a temperature variation from 25°C to 65°C for a voltage up to 65Volts. Above this value the current decreases in a sharp manner for small variation in voltage. It is further seen that the voltage of which the cell current becomes zero increases with decreasing temperature. The voltage and power characterstics are presented in Fig.11.

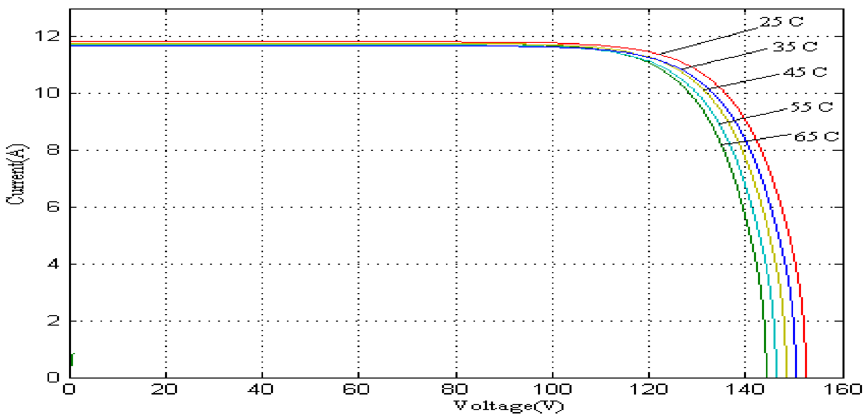

Fig. 10 V-I characteristics of PV module for different cell temperatures at rated intensity.

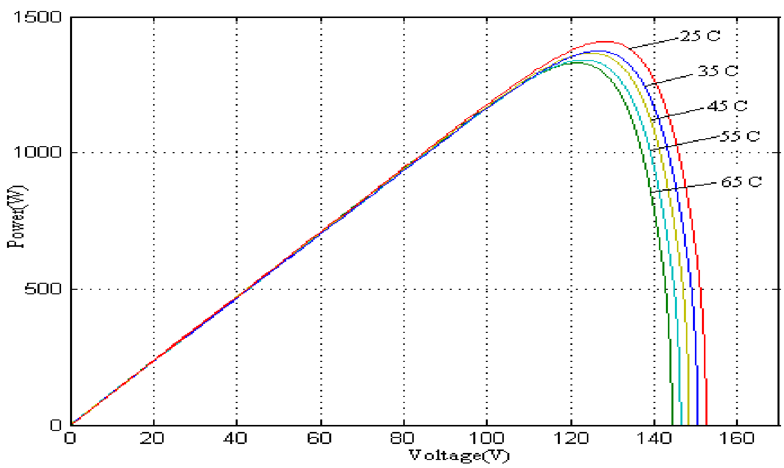

Fig. 11 PV Curve with Temperatures Variation

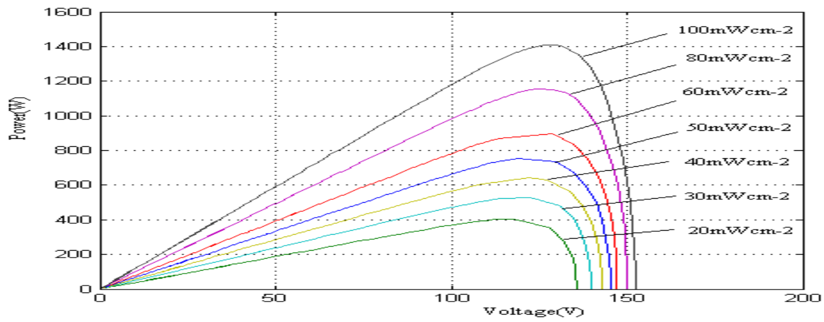

Fig. 12 PV Curve with different irradiation

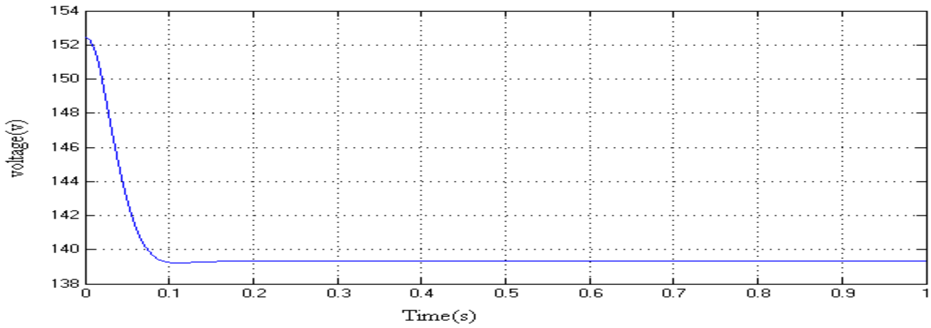

Fig. 13 Output voltage response of PV array

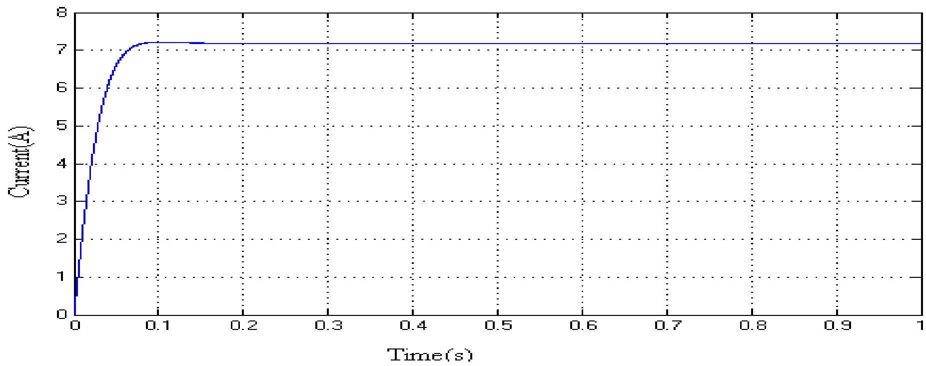

Fig. 14 Output current response of PV array

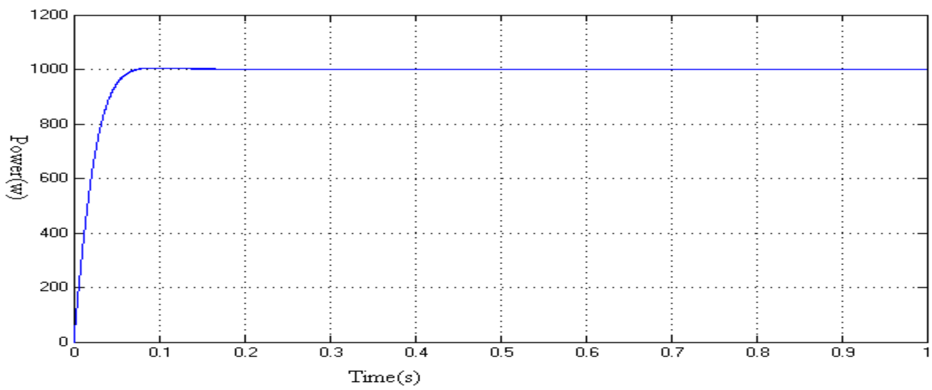

Fig. 15 Output Power response of PV array

5. CONCLUSION

Solar cells in PV array work only in part of volt-ampere Characteristic near working point where maximum voltage and maximum current is. We assume that photovoltaic system works most of time with maximum efficiency. It means that for modeling of PV cell we should use constants for specific kind of cell near working point.

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